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FORGING AND STAMPING
(Selected Articles)

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

NEW TECHNOLOGY FOR PRODUCING FORGINGS FOR LARGE TURBINE DISCS

I.G. Generson, P.D. Khinskiy, V.N. Tokarev, P.M. Libman, V.N. Krylov.

The production of forgings of chromium-nickel steel for large turbine discs with hubs up to 600-650 mm thick is a complex task. The main difficulties in this case are associated with the need to assure high specifications with respect to purity, macrostructural homogeneity, and the mechanical properties of the metal within the interior layers of the forged piece. We know of cases where discs have failed during operation as a result of stress concentrators of metallurgical origin resulting from the presence of nonmetallic inclusions and reduced plasticity and ductility of the metal in the central zones of the disc. Because of this a rigid quality control system was established for the metal, which includes mechanical tests and ultrasonic flaw detection. Existing monitoring methods do not offer comprehensive information on the quality of the metal within

interior layers of the forged piece inacessible to direct testing. However, it is precisely these layers which are generally weakened by undetected metallurgical defects, first among which is gas saturation. The larger the piece, the more serious the effect of this factor. Thus, one of the invariable conditions of positive evaluation for production technology of forgings for large turbine discs is the high level of the mechanical properties of the metal within its interior zones.

Until recently the production technology of large forgings for turbine discs was based on the following:

1. Steel for the forgings was melted in an a martensite acid furnace. This assured minimal gas saturation of the metal and a desirable composition of nonmetallic inclusions.

2. The steel was poured into ingots of minimal possible weight (calculating a yield of one disc per ingot) in air, without vacuuming.

3. Forging was done by broaching the billeted and upset (forged) block with drawing on a mandrel.

4. The forged discs were cooled with prolonged isothermal

holding at 600-650° C. Generally, for additinal removal of hydrogen from the metal in a solid state the billet was also annealed in an intermediate forging stage - after upsetting, broaching, and drawing of the block on the mandrel [broach].

As a result of studying several discs produced by this method (including used discs), it was discovered that in the case where regular monitoring produced satisfactory results the metal in the interior zones of the forgings had low plasticity indicators, primarily as the result of hydrogen brittleness. For example, a disc with a hub thickness of 4 mm, forged from an ingot with a mass of 10 T, after sectioning and rapid testing had the following mechanical property values in the interiors zones of the hub (Table 1).

(1) Направление образца	$\sigma_{0,2}$ в кгс/мм² (2)		δ в % (3)		ψ в %	
	(4) минимальный	(5) средний	минимальное	среднее	минимальное	среднее
(6) Тангенциальное	72,2	73,2	13,1	14,5	23,4	27,3
(7) Осевое	69,5	72,9	5,5	6,3	7,6	9,0

Table 1. Key: 1 - direction of specimen, 2 - in kgf/mm², 3 - in °/o, 4 - minimal, 5 - average, 6 - tangential, 7 - axial.

When the specimens were broken a large number of floccules were discovered, indicating a high degree of gas saturation on the part of

the metal.

To decrease this gas saturation and hydrogen brittleness a technological process for producing forgings from acid martensitic steel with vacuuming during casting was tested and introduced into practice for the largest discs (hub thickness of 620 mm). However, to achieve vacuuming a twofold increase in the weight of the billet was necessary for a yield of two discs per billet. When the forgings produced by this method were studied, it was established that hydrogen brittleness in the interior layers of the disc had decreased, but that there had been a simultaneous increase in the liquation [segregation] heterogeneity of the metal.

At the Neva Machine Building Plant im. V.I. Lenin a series of studies was undertaken on a new method of producing forgings for large turbine discs which would assure the high quality of the metal.

The technological features of the new process are as follows.

1. Used for the production of discs is steel which has been melted in an electric arc furnace by the method of deep decarburization.

2. When it is poured into ingots of relatively low weight,

designed to yield one disc each, the steel was vacuumed.

3. An increased volume of metal was removed from the axial zone of of the ingot.

Presented below are the characteristics of the main stages of the experimental operation in the production of forgings for large turbine discs according to the new technological process and results of studies performed on them. Also presented for comparison are data from a study on analogous forgings prepared by the old method.

Fig. 1 shows a diagram of the experimental forgings for discs with a hub thickness of 620 mm (A) and 440 (B).

Steel 34KhN3MA for the forgings was melted in a 40-ton electric arc furnace by a method which was approximately as follows: The concentration of carbon in the bath with 0.6 $^0/_0$ or above after melting was first decreased to 0.3-0.4 $^0/_0$, then the metal was carburized to the brand composition and the necessary deoxidation and alloying performed. As experiments have shown, during melting of steel by the deep decarburization method, the hydrogen content in the steel drops from 7-8 to 3.5-4.5 $cm^3/100$ g as compared to the standard melting method.

To obtain a more favorable composition and form of nonmetallic inclusions the composition of the deoxidizers was changed: In place of the former aluminum, blast ferrosilicon and silicomanganese not containing aluminum were used. Through a study it was established that in this case nonmetallic inclusions consist almost entirely of silicates with a high concentration of silica, that they are deformed little during forging, and that they have no significant effect on lowering of the mechanical properties of the metal.

The steel is poured into ingots in a vacuum with rarefaction in the chamber of up to 0.2-0.4 mm Hg. created by a powerful five-stage steam-ejection pump. The weight of the selected ingots: 16.4 and 8.36 T with a ratio of H/D_{cp} = 1.99 and a conicity of 8 $^0/_0$ (for discs of types A and B, respectively) and 7.6 T with a ratio of H/D_{cp} = 2.13 and a conicity of 3.1 $^0/_0$ (for discs of type B).

For experimental sutdies ingots with masses of 16.4, 8.36, and 7.6 T were poured from different melts.

The chemical composition of the melts in shown in Table 2.

The concentration of hydrogen in electric steel melts prior to vacuuming was within limits of 3.7-4.5 cm^3/100g, after vacuuming - about 2 cm^3/100 g.

The ingots were transfered from the steel smelting shop to the forging and pressing shop in a hot state with a surface temperature of about 600-670°C and were heated to forging teperature according to existing plant instructions.

All discs were forged on a 3000 ton-force press. Figures 2 and 3 show the sequence of forging operations in producing forgings for discs from ingots with a mass of 16.4 and 7.6 T.

Changes in the technological process of forging discs of type A as compared to the old technology occured in operations related to removal of the axial zone of the ingot: The diameter of the broached opening in operation 4 (see Fig. 2) has increased by 50 mm, drawing of the billets on the mandrel brought to 1300 mm (corresponding length in old variation is 1100 mm), which causes an increase in the volume of secondary metal scrap removed in operation 6.

The distinguishing feature of the forging technology for a disc of type B was the additional broaching of the billet in an intermediate upsetting stage (operation 2), which made it possible to increase the volume of metal removed from the axial zone of the ingot by 50-60 %.

To reduce the degree of propagation of the the axial zone of the ingot radially toward the periphery, forgings of both types were finally formulated by upsetting to a height equal to that of the disc hub with subsequent fullering of the web on two sides by sliding [strike] blocks.

The regimes of intermediate annealing and primary heat treatment of the forgings corresponded to analogous regimes used for discs of acid martensitic steel.

The final heat treatment of the discs (after roughing) was as follows: normalization from 900-905° C, hardening from 850-870°C with oil cooling, tempering at 590-630° with slow cooling in the furnace.

The billets were subjected to all types of control - called for by technical specifications for turbine disc forgings in OTU-24-10-003-68. With respect to their mechanical properties the discs satisfied the TU norms, while the plasticity and impact resistance indicators exceeded the norms by a broad margin. By studying the macrostructure of the discs through inspection of etched hub surfaces and central openings and by sulphur imprints taken from these surfaces the absence of any discontinuities in the metal and of

nonmetallic inclusions not tolerated by technical specifications was established. On the sulphur imprints a uniform distrubution of sulphur was observed, corresponding to 1-2 points on the NKMZ scale. Bearing in mind that the number of points of the sulphur imprint from the surface describes the surface yield of liquation strings, it was possible in this monitoring stage to establish the absence of a strongly developed off-center liquation in the discs.

Ultrasonic monitoring of billets is done on the UZD-7N device at a frequency of 2.5 mHz using straight and slanted scanners [finders]. Slanted scanners detect the most dangerous defects - those oriented in the radial-axial plane, which are the cause of tangential stress concentration during operation. In none of the experimental electric steel discs were any defects in the metal detected. Note than in virtually all type-A discs forged from acid martensitic steel, particularly the nonvacuumed, ultrasound produces defects and zones where defects accumulate. The latter usually consist of large flattened sulfide inclusions and films of complex oxides.

For a more detailed study of metal quality one type-A disc (melt 840631) and two type-B discs (melts 6764 and 840 651) were cut open and studied. In this case the degree of nonuniformity over the disc section, mechanical properties within interior zones and various directions, and the transient embrittlement temperatures were

determined.

The macrostructure of the metal over the disc section was studied on radial-axial templets. In examining ground and etched surfaces no visible metal defects were observed on any templet. On sulfur imprints taken from the templets a generally even distribution of sulphur, corresponding to 1-2 points on the NKMZ scale and traces of liquation strings w· e observed.

In the type-A disc the width of the liquation strings, which lie at an anle to the disc bore, constitutes about 3 mm. An analogous disc, prepared by the existing technology from vacuumed martensitic steel, is distinguished by its more developed off-center liquation. In the given case the width of the strings reaches 10 mm. This is apparently related to the greater weight of the ingot used to prepare the two discs.

The experimental type-B discs are distinguished by a lower degree of liquation. The best results - almost total absence of liquation heterogeneity - were found in the disc forged from a 7.6 T ingot. An analogous pattern is observed in discs of nonvacuumed martensitic steel.

We know that large liquations strings in the discs are sensitive

to a bending probe. Ten specimens from the places of greatest concentration of strings on the experimental disc were selected and tested for bending. All specimens passed the tests at a bending angle of 150° - additional evidence of the relatively moderate development of off-center liquation in experimental discs prepared according to the new technological process.

From various portions of a radial-axial templet of a type-A disc which characterized the hub region near the bore, specimens were selected for the prupose of finding and studying nonmetallic inclusions. The total quantity of nonmetallic inclusions was determined at 0.0075 $^0/_0$. Metallographic analysis was used to establish the presence of large inclusions of complex composition. Contamination by impurities such as sulfides was estimated at 1-2 points and by oxides at 1 point per GOST 1778-62. On the basis of reduced data the concentration of nonmetallic inclusions in the disc metal was estimated as insignificant.

Discs selected for detailed study were subjected to a test of the mechanical properties of the metal in the interior zones of the hub as most characteristic with respect to relaible evaluation of the quality of the forging. Hollow drills were used to cut rods 94 mm in diameter from the central part of the hub. From these tensile and impact test specimens were taken tangentially and tensile specimens

axially. Impact test specimens were cut axially from the rod of the type-B disc (forging No. 11 - Table 3).

In preparation of large forginings the metal of the interior zones may be subject to hydrogen embrittlement, which is expressed in low plasticity indicators δ and ψ with formation in many cases where tensile test specimens are broken of light colored spots - tension floccules. Yet as a result of the relatively high diffusion rates of hydrogen in chromium-nickel-molybdenum steel at room temperature, in the standard slow methods of cutting discs and preparation of specimens at room temperature hydrogen brittleness does not appear. Thus, for correct estimation of the plasticity of a metal with the effect of hydrogen considered, specimens were prepared over a total time not exceeding 24 h. Parallel tests were conducted on specimens taken from these discs after prolonged holding at room temperature. Impact test specimens were not subjected to immediate tests, considering the fact that the presence of hydrogen in the steel has no significant effect on impact toughness and the transient brittleness temperature.

Used in the tensile test were specimens 8 mm in diameter with a calculated length of 40 mm. Specimens of type 1 per GOST 9454-50 were used to test impact toughness.

999tab The results of mechanical tests conducted on specimens cut from the interior layers of disc hubs (see Table 3), are evidence of the high level of plasticity in the metal of disc forgings produced by the new technology. Note the high level of plasticity of the metal even in tests on axial specimens.

In Table 3 we also find the results of tests by an analogous method on discs prepared by the old technology. Most interesting here is a comparison of the mechanical properties of the metal of the deep layers of the discs after rapid tests.

At practically the same yield point and strength values higher plasticity values are observed for the metal of discs of type B, in which the ψ values on tangential specimens is approximately twice as great , on axial specimens - almost four times as great, as on discs prepared by the old technology. The types of breaks are sharply distinguished among specimens taken from these discs. In the first case tension floccules do not appear in a single specimen. After the specimens are broken there is a very pronounced neck; the breaks are cup-shaped and fibrous. In the second case almost all specimens displayed light colored spots - tension floccules, and the specimens had either a poorly defined neck or no neck at all.

In type A discs the difference in plasticity properties is not

as substantial, although here we do clearly observe the advantages of forgings prepared by the new technology.

After aging, the mechanical properties of specimens from the metal of discs prepared by different technological processes was close in the tangential direction (explained by the absence of the embrittling effect of the hydrogen), but retained distinct differences in the axial direction. In this case we no longer perceive the effect of the degree of gas saturation of the steel, rather the effect of other technological factors which specifically affect the quantity, composition and distribution of nonmetallic inclusion in the metal of the disc.

Table 4 shows the coefficients of isotropy for plasticity indicators δ and ψ of an interior zone in various discs, determined as the ratio of properties in the axial direction to properties in the tangential direction. The coefficients of isotropy are calculated from the average values of δ and ψ.

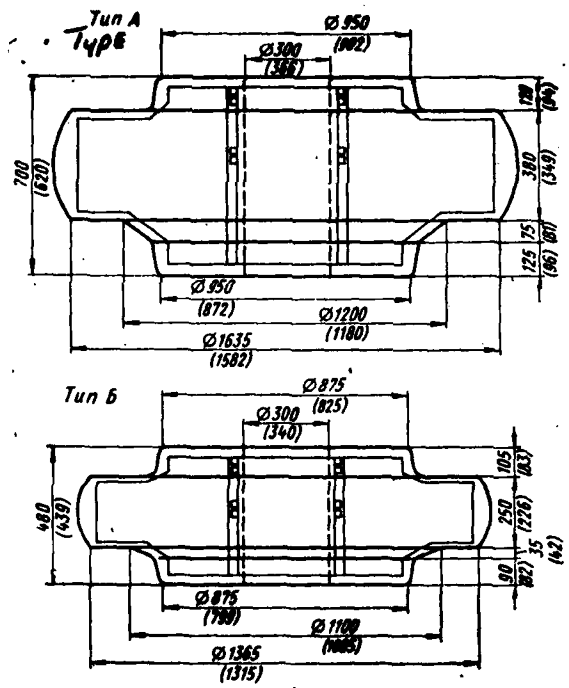
One important reliability criterion for disc metal (considering the possible presence in them of stress concentrators) is transient brittleness temperature T_{K}. In the studied discs T_{K} was determined by taking impact test specimens from the central zones of the hubs and tests at different temperatures with registration of the percent

of fiber in breaking. Criterion $T_к$ was the presence in the break of 50 $^{0}/_{0}$ fiber. The obtained $T_к$ values for discs of different goups are shown in Table 5, from which the advantages of discs produced by the new technology become obvious.

Thus, as a result of experimental research a number of positive characteristics were established for the forgings of large turbine discs prepared by the new method. These include: a significantly higher level of plasticity characteristics, a much higher degree of isotropy on the part of the mechanical properties, a low transient brittleness temperature. In the largest discs (hub thickness of 620 mm) off-center liquation is less developed.

This new technological process of preparing forgings for large turbine discs, which was first implemented in the USSR at the Neva Machine Building Plant im. V.I. Lenin, assures discs of high quality, reduces the tendency toward brittle fracture, and increases their operational reliability.

Fig. 1. Diagrams of experimental forgings for discs with hub thickness of 620 mm (A) and 440 (B) (roughing dimensions for heat treatment shown in parentheses).



Баланс металла		Сталь	Усилие пресса	Температурный интервал ковки
Слиток Поковка Выход годного	16400 кг 8650 кг 53%	34ХН3МА	3000 тс	1200–700°С

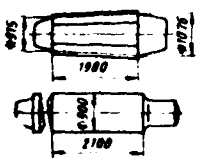
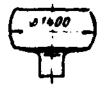
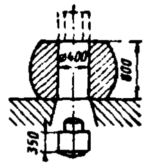
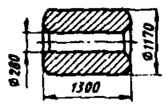
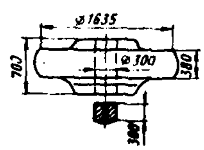
№ операции	Переходы	Эскизы переходов	Инструмент
1	Ковка цапфы Протяжка слитка на Ø 900 мм Рубка нижней части слитка		Бойки: Верхний—плоский Нижний—вырезной
2	Осадка до диаметра 1400 мм		Осадочные плиты
3	Протяжка на Ø 900 мм Рубка заготовки		Бойки: Верхний—плоский Нижний—вырезной
4	Осадка до высоты 800 мм. Прошивка отверстия Ø 400 мм пустотелым прошивнем		Осадочные плиты Прошивные плиты Пустотелый прошивень Ø 400 мм
5	Вытяжка на оправке Ø 280 мм до длины 1300 мм		Коническая оправка Ø 280 мм
6	Промежуточный отжиг		
7	Обкатка заготовки на оправке Ø 200 мм. Осадка до h=720 мм. Разгонка полотна с двух сторон. Прошивка отверстия Ø 300 мм. Отделка поковки		Коническая оправка Ø 200 мм. Раздвижные бойки. Прошивень Ø 300 мм

Fig. 2.

Fig. 2. Technological forging scheme for disc from ingot with mass of 16.4 t (type A). Key: (1) metal balance, (2) steel, (3) press force, (4) forging temperature interval, (5) ingot/forging/ acceptable yield, (6) kg, (7) 34KhN3MA, (8) ton force, (9) °C, (10) No. of operation, (11) transitions, (12) transition diagrams, (13) tool, (14) forging of journal/drawing of ingot 900 mm in diameter/ cut-off of lower portion of ingot, (15) strikers: upper -flat, lower - recessed, (16) reduction to diameter of 1400 mm, (17) reduction plates, (18) drawing to diameter of 900 mm/ cut-off of billet, (19) strikers: upper -flat, lower - recessed, (20) reduction to height of 800 mm. Broaching of aperture of diameter 400 mm by hollow forging punch, (21) Reduction plates/ broaching plates/ hollow forging punch 400 mm in diameter, (22) Drawing on mandrel of diamter 280 mm to length of 1300 mm, (23) Conical mandrel of diameter 280 mm, (24) intermediate annealing, (25) rolling on mandrel 200 mm in diameter. Reduction to h = 720 mm. Fullering of web on two sides. Piercing of aperature of 300 mm in diameter. Dressing of forgiing, (26) Conical mandrel 200 mm in diameter. Sliding strikers [blocks]. Forging punch 300 mm in diameter.

Table 2. Key: (1) No. of melt, (2) chemical composition in %, (3) weight of cast ingots, t, (4) electric steel, (5) martensitic acid steel.

1 № плавки	2 Химический состав в %									3 Развес отлитых слитков в т
	C	Si	Mn	S	P	Cr	Ni	Mo	Cu	
4 Электросталь										
840 631	0,32	0,29	0,60	0,009	0,017	0,96	2,77	0,36	0,10	16,4
6 764	0,33	0,28	0,65	0,014	0,023	0,87	3,00	0,32	0,10	8,36
840 651	0,33	0,27	0,60	0,012	0,021	0,93	3,00	0,36	0,08	7,6
940 739	0,36	0,23	0,58	0,012	0,016	0,95	3,02	0,31	0,16	8,36
840 018	0,36	0,28	0,61	0,012	0,024	0,92	2,64	0,33	0,11	8,36
840 615	0,31	0,28	0,62	0,017	0,020	0,90	3,00	0,30	0,08	8,36
5 Кислая мартеновская сталь										
47 216	0,33	0,20	0,55	0,020	0,010	1,14	2,93	0,36	—	26,7
48 920	0,37	0,28	0,60	0,018	0,015	0,97	2,90	0,38	0,09	10,0
49 650	0,38	0,31	0,64	0,018	0,017	0,89	2,77	0,38	0,09	10,0

Баланс металла		Сталь	Усилие пресса	Температурный интервал ковки
Слиток Поковка Выход годного	7600 кг 4300 кг 57%	34ХН3МА	3000 тс	1200—700°C

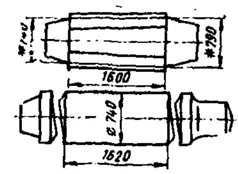
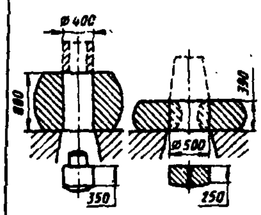
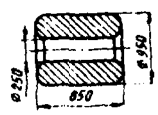
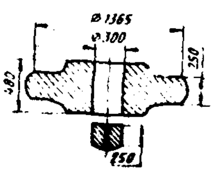
№ операции	Переходы	Эскизы переходов	Инструмент
1	Ковка цапфы Протяжка слитка на круг Вырубка заготовки		Бойки: Верхний плоский Нижний — вырезной
2	Первая осадка заготовки до высоты 800 мм Прошивка отверстия диаметром 400 мм. Вторая осадка заготовки до h= 390 мм. Вторая прошивка отверстия диаметром 500 мм		Осадочные плиты Прошивные плиты Пустотелый прошивень Ø 400 мм Сплошной прошивень Ø 500 мм
3	Вытяжка заготовки на оправке с заковкой отверстия до Ø 250 мм		Коническая оправка Ø 250 мм
4	Промежуточный отжиг		
5	Осадка заготовки до высоты 500 мм Разгонка полотна раздвижными бойками с двух сторон Прошивка отверстия в поковке		Осадочные плиты Раздвижные бойки Прошивень Ø 300 мм

Fig. 3.

Fig. 3. Technological forging scheme of disc from ingot with mass of 7.6 t (type B). Key: (1) metal balance; (2) steel; (3) press force; (4) forging temperature range; (5) ingot/forging/ acceptable yield; (6) kg; (7) 34KhN3MA; (8) ton force; (9) No. of operation; (10) transitions; (11) transition diagrams; (12) tool; (13) Forging of journal/ drawing of ingot into circle/ cut-off of billet; (14) strikers: upper flat, lower recessed; (15) First reduction of billet to height of 800 mm. Piercing of opening 400 mm in diameter. Second reduction of billet to height of h=390 mm. Second piercing of opening 500 mm in diameter; (16) Reduction plates/ broaching plates/ hollow forging punch with diameter of 400 mm/ Solid forging punch with diameter of 500 mm; (17) Drawing of billet on mandrel with compression of opening to diameter of 250 mm.; (18) conical mandrel with diameter of 250 mm; (19) intermediate annealing; (20) Reduction of billet to height of 500 mm. Fullering of web by sliding strikers [blocks] on both sides. Piercing of opening in forging; (21) Reduction plates/sliding strikers [blocks]/ forging punch with diameter of 300 mm.

Table 3. Mechanical properties of metal of interior disc zones.

Key: (1) No. of disc/ No. of melt; (2) technology; (3) melting and casting method; (4) direction of specimen; (5) after immediate tests; (6) after aging of specimens; (7) in kgf/mm²; (8) limit deviation; (9) average; (10) discs with hub thickness of 620 mm (type A); (11) new; (12) electric steel, vacuumed; (13) tangential; (14) axial; (15) old; (16) martensitic steel, vacuumed; (17) discs with hob thickness of 440 mm (type B).

1 № диска / № плавки	2 Технология	3 Метод выплавки и условия разливки	4 Направление образца	5 После быстрых испытаний								6 После выдерживания образцов									
				$\sigma_{0,2}$ в кгс/мм² (7)		$\sigma_в$ в кгс/мм²		δ в %		ψ в %		$\sigma_{0,2}$ в кгс/мм²		$\sigma_в$ в кгс/мм²		δ в %		ψ в %		$a_н$ в кгс/см²	
				8 предельное отклонение	9 среднее	предельное отклонение	среднее	предельное отклонение	среднее	предельное отклонение	среднее	предельное отклонение	среднее	предельное отклонение	среднее	предельное отклонение	среднее	предельное отклонение	среднее	предельное отклонение	среднее
10 Диски с толщиной ступицы 620 мм (тип А)																					
10 / 640 631	11 Новая	12 Электросталь, вакуумированная	13 Тангенциальное	63,8—67,3	66,0	83,3—85,8	84,9	15,6—18,3	17,4	56,8—60,9	58,0	62,1—70,8	65,9	82,0—88,0	84,7	18,2—22,0	18,6	53,0—64,8	61,0	11,1—13,5	12,3
			14 Осевое	62,6—66,6	65,1	83,5—89,5	85,2	13,3—18,1	15,9	42,1—54,2	47,3	63,0—67,6	64,7	81,1—87,4	84,9	15,7—18,9	17,6	53,0—57,0	54,7	—	—
20 / 47 216	15 Старая	16 Мартеновская сталь, вакуумированная	Тангенциальное	62,1—69,8	64,8	80,7—88,1	84,0	13,8—15,9	14,9	36,8—45,8	40,7	60,8—64,5	62,5	79,2—84,4	82,1	16,2—21,4	18,3	52,7—58,1	55,1	7,4—8,0	7,6
			Осевое	64,0—68,8	66,6	83,0—85,5	84,5	4,3—11,8	9,4	10,4—28,6	20,8	63,7—67,0	64,7	82,4—87,0	84,1	14,4—15,8	15,0	40,4—49,7	44,5	—	—
17 Диски с толщиной ступицы 440 мм (тип Б)																					
11 / 6 784	Новая	Электросталь, вакуумированная	Тангенциальное	70,2—87,0	78,0	87,7—93,0	90,8	17,0—19,3	18,4	48,6—59,9	56,9	70,7—80,2	76,6	88,6—95,2	92,0	18,0—21,0	18,7	55,9—62,3	58,6	11,2—14,3	12,7
			Осевое	70,7—74,8	73,0	86,7—90,0	89,4	13,3—18,7	15,8	33,0—55,6	46,7	71,1—76,4	73,8	87,2—92,2	89,6	12,3—19,0	15,7	41,8—62,3	52,1	8,8—15,8	10,5
12 / 640 651			Тангенциальное	63,0—68,9	67,3	84,2—88,5	85,9	16,5—20,4	17,6	52,2—60,0	56,4	68,3—73,5	70,9	84,3—86,4	85,5	16,8—19,1	18,6	55,7—61,0	58,4	8,6—11,4	10,0
			Осевое	68,4	68,4	83,2	83,7	15,0	15,0	47,8	77,8	63,0—66,0	64,4	80,3—85,3	82,8	16,5—19,5	17,9	43,8—59,0	53,6	—	—
21 / 46 920	Старая	Мартеновская сталь, разливка на воздухе	Тангенциальное	72,2—74,4	73,2	88,6—92,3	90,5	13,1—15,6	14,5	23,4—30,0	27,3	66,8—70,4	68,8	83,5—90,5	86,7	17,0—18,1	17,5	58,4—60,4	57,5	7,1—7,7	7,4
			Осевое	69,5—74,0	72,9	86,4—88,7	87,3	5,5—7,0	6,3	7,6—10,0	9,0	58,4—71,2	70,2	88,3—89,6	89,1	9,3—12,3	11,1	27,4—30,2	26,0	—	—
22 / 46 680			Тангенциальное	69,4—74,0	71,8	92,1—96,8	90,4	11,0—15,8	14,4	27,4—28,6	28,3	64,4—75,8	71,1	90,6—94,7	94,2	14,1—17,4	15,9	49,7—60,7	55,7	4,1—4,6	4,3
			Осевое	70,6—72,6	71,9	88,4—91,1	89,6	6,0—7,5	7,0	9,8—14,4	10,9	64,8—70,7	68,7	89,7—91,4	90,3	10,8—11,9	11,3	38,0—39,1	38,2	—	—

Table 4. Coefficient of isotropy according to plasticity indicators δ and ψ in interior disc zones. Key: (1) technology; (2) No. of forging; (3) coefficient of isotropy; (4) prior to aging of specimen, (5) after aging of specimen; (6) new /old; (7) discs with hub thickness of 620 mm (type A); (8) new; (9) discs with hob thickness of 440 mm (type B); (10) old.

1 Технология	2 № поковки	3 Коэффициент изотропии			
		4 до вылеживания образца		5 после вылеживания образца	
		δ	ψ	δ	ψ
6	7 Диски с толщиной ступицы 620 мм (тип А)				
Новая Старая	10 20	0,91 0,63	0,80 0,51	0,95 0,82	0,90 0,81
8	9 Диски с толщиной ступицы 440 мм (тип Б)				
Новая	11 12	0,86 0,85	0,82 0,85	0,84 0,96	0,89 0,92
10 Старая	21 22	0,43 0,49	0,83 0,34	0,63 0,71	0,61 0,59

Table 5. Transient brittleness temperature. Key: (1) hob thickness of discs in mm; (2) technology; (3) new; (4) old.

1 Толщина ступицы дисков в мм	2 Технология	$T_к$ в °C
620	3 Новая	0
	4 Старая	+30
440	Новая	−40 +15
	Старая	+40 +80

PRODUCTION OF LONG-AXIS FORGINGS BY STRETCHING IN STATE OF SUPERPLASTICITY

Ya.M. Okhrimenko, O.M. Smirnov, V.P. Balakin, V.A. Boytsekhovskiy, V.Ye. Shklyayev.

The state of superplasticity creates conditions favorable to pressure treatment of metals. Achievement of a high degree of deformation [strain] without failure under conditions of insignificant specific forces makes it possible to employ deformations which depart from the traditional system and on this basis to create effective technological processes.

For example, the process of uniaxial tension is rarely used as a basic forming operation because of early loss of stability and the

impossibility of obtaining uniform elongations of sufficient magnitude in metals with standard plastic deformation. In the case of deformation in a state of superplasticy uniform elongations of several hundred, sometimes a thousand, percent can be obtained. This high uniform deformation permits use of the stretching process as an independent forming operation. The basis of this process is the system of so-called "die-free drawing" [1-2].

The billet bar or wire 2 (Fig. 1a) is clamped between two grippers 1,4 and passes along ring inductor 3, in which a narow zone of the metal is heated to the required temperature. When tensile force P, sufficient for metal flow in the heated zone, is applied to the bar or wire, the billet begins to narrow. To avoid failure of the metal at the narrowed place after its deformability has been expended, the heating zone must be shifted. As a result temperature in the narrowed zone decreases, resistance to deformation increases, narrowing ceases, and deformation occurs in the zone of higher temperature. The place where deformation begins can be shifted by shifting the heating zone. In a steady tension process the connection between the rate of movement of the heated zone v_2 and the speed at which the metal emperges from the inductor (in the present deformation system this is composed of of the velocity of moving capture v_1 and the rate of movement of inductor v_2) will determine the ratio of areas of the original and deformed section of the bar:

(1) $$\frac{v_1+v_2}{v_2}=\frac{S_0}{S_\kappa}=\frac{d_0^2}{d_\kappa^2},$$

where v_1 is the rate of movement of the stretching gripper; v_2 - rate of movement of the inductor; S_0, S_κ - areas of original and final bar sections; d_0, d_κ - original and final diameters of bars.

If the heating unit is stationary, then a different variation of the kinematic system is used: Both grippers must move in the same direction, but at different speeds. Here the formula takes the form of

(2) $$\frac{v_1}{v_3}=\frac{S_0}{S_\kappa}=\frac{d_0^2}{d_\kappa^2},$$

where v_3 represents the rate of movement of the feed gripper.

The ratio of the area of the bar cross section before and after deformation is represented by the drawing coefficient

(3) $$\mu=\frac{S_0}{S_\kappa}=\frac{d_0^2}{d_\kappa^2}=\frac{l_\kappa}{l_0},$$

where l_0 and l_K - represent the length of the bar before and after deformation.

We know that a state of superplasticity is generally attained by two methods:

a) by deformation of the metal or alloy during the process of phase conversin or any other diffusive (sometimes nondiffusive) process associated with rearrangement of the crystal lattice;

b) by deformation of an alloy reduced to a fine-grained structureal state (grain dimension no greater than 1-5 μm) at a temperature below that of collective recrystallization.

Another very important condition for obtaining the state of superplasticity is the creation of certain deformation rate conditions. As a rule the rate of deformation lies within the range of 10^{-4}-10^{-2} s^{-1}.

Widely used for the purpose of determining optimal deformation regimes in a state of superplasticity is a method in which the criterion of the state of superplasticity is coefficient m, describing the sensitivity of the resistance to deformations σ to the rate of deformation $\dot{\varepsilon}$. Under conditions corresponding the standard

procedures coefficient m does not exceed 0.2. In absolutely viscous bodies (for example, heated glass, certain types of of plastics) m equals 1. Superplastic metals have a coefficient of $0.3<m<1$.

At the present time several methods are used to determine m as a result of mechanical tests [3,4]. After preliminary studies of the optimal conditions for a state of superplasticity and determinatin of the main deformation parameters: deformation temperature interval T $T_{нижн} \div T_{верх}$, deformatin rate $\dot{\varepsilon}$ resistance to deformation σ, and relative elongation δ_{max} prior to formation of the neck, we can proceed to plot the technological forming process, in this case the process of uniaxial stretching employing one of the kinematic systems below.

These systems can be broken down into two groups: those with moving heating unit (Fig. 2a) and those with stationary heating unit (Figs. 2b,c,d).

The use of each system is determined by the designation of the device: bars and profiles can be formed, for example, by the systems shown in figures 2a,b,c; wire and strip - by the system shown in figure 2c. These systems cover only a portion of the wide range of variations which can be used in designing devices for forming under tension.

One of the main features of these devices is their small energy consumption. In a state of superplasticity resistance to strain is lower than in standard hot forming. Moreover, strain occurs under contactless conditions, which eliminates friction between the billet and tool.

At the same time, to assure the accuracy of dimensions in the article accuracy requirements for regulation and stability in the rate of the drawing and feed mechanisms are increased. There are several variations of the gripping and transporting mechanisms (see Fig. 2): pulling grippers (see Fig. 2 c), where the speed difference is created either by the difference in diameters of drums rotating at the same angular speed or by the different angular speeds of the drums. The basic requirement for the drives is smoothness and accuracy in regulation over rather broad limits. Regulation accuracy is particularly important in the case where the speed ratio of the pull and feed mechanisms must be changed in the production of articles with a longitudinally variable cross section.

Force and speed parameters can be monitored by standard or special force and speed sensors.

In Fig. 1b we see diagrams representing the change in the main parameters during the initial stage of deformation and during steady flow of the metal.

Heating of the metal is one of the most important and complicated problems of deformation in a state of superplasticity. The main requirements for heating are: high degree of accuracy in maintaining assigned temperature in heating zone, minimal temperature nonuniformity over cross section, high heating speed. Induction heating best conforms to these specifications. Moreover, this is a heating method which involves little scale formation.

At the Moscow Institute of Steel and Alloys workers have contributed their efforts to the creation of laboratory devices with the schemes shown in figures 2a and b for the purpose of studying and developing technological processes for forming metals in the superplastic state under uniaxial tension. Positive results were obtained, thus demonstrating that under optimal temperature-rate conditions of superplasticity it is posible to deform metal by tension with a degree of drawing of 400-800 %, with highly precise final dimensions.

In figure 3 we see examples of articles produced under tension in a state of superplasticity.

At the present time more than 100 metals and alloys are known to have superplasticity under certain conditions. Their number should, apparently, increase, and there will be new technological solutions for the use of the superplastic state. Forming by uniaxial tension is one way to use the superplasticity phenomenon, which provides a number of important advantages over standard drawing.

1. Large drawn articles can be obtained is one pass without intermediate annealings.

2. Much less force is required for deformation.

3. It is not necessary to prepare a working tool, which is often costly and time consuming. Its strength during machining of of hard-to-work metals is also low.

4. There is no lubrication problem.

5. Induction heating makes it possible to obtain an article with a high quality surface.

6. Easy transition from one article to another gives this method

great advantages, particularly in small-series and individual production.

Broadscale adaptation of the procedure is being held back by insufficient data on the flow conditions of the metal at the place where deformatin begins, the limited number of metals and alloys for which methods of creating superplasticity conditions have been determined, and the relatively low strain rates (10^{-4}–10^{-2} s^{-1}). Further research will undoubtedly make in possible to eliminate some of these limitations.

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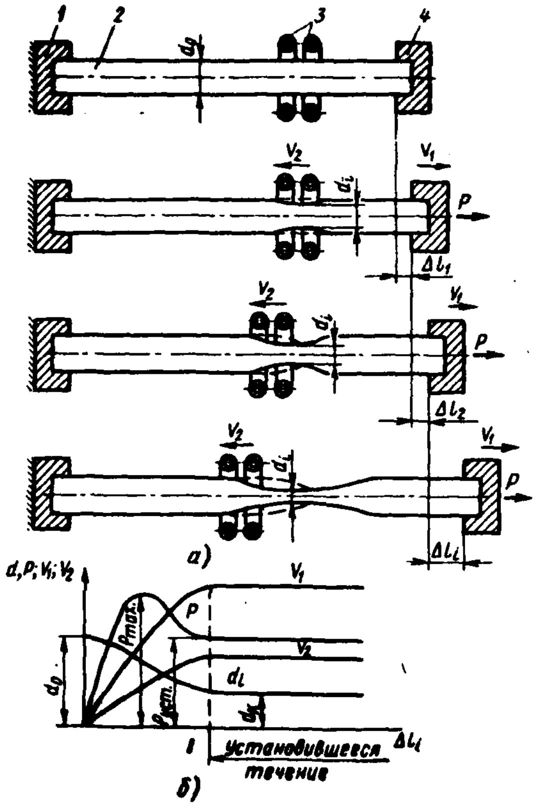


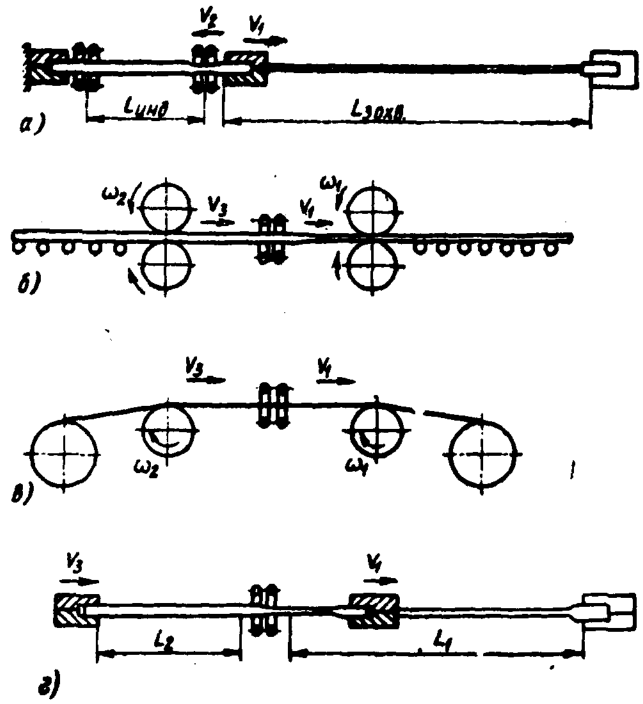
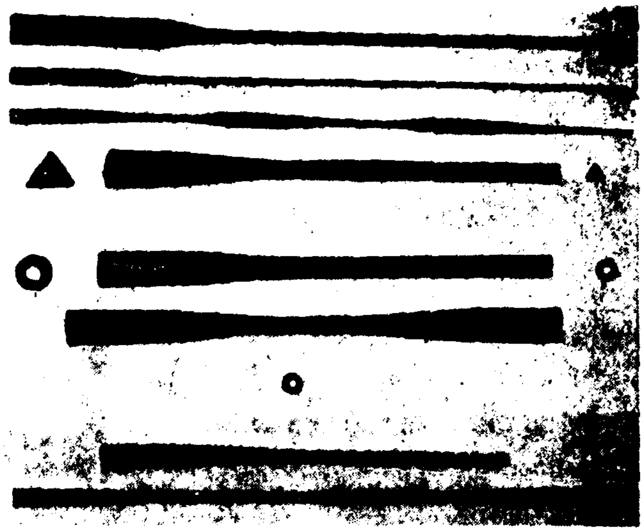


Fig. 1. Forming states during stretching. Key: 1 - steady flow.

Fig. 2. Possible kinematic schemes for tension forming devices.

Fig. 3. Examples of articles obtained by stretching in state of superplasticity.



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